A REVIEW OF FISH ECOLOGY MODELS AND AN APPROACH FOR INTEGRATED RESERVOIR AND ECOLOGICAL MANAGEMENT

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Abstract. Many species of fish have suffered detrimental impacts due to the construction and operation of reservoirs. Life-scientists have utilized three basic methods to attempt to include the needs of riverine ecology in the formulation of reservoir operation policies. (1) Beginning in the 1970's, discharge-based methods used heuristics to determine minimum allowable streamflows to protect riverine life. (2) Habitat-based models were developed after the shortcomings of minimum allowable streamflow recommendations were realized and as greater knowledge of fish biology and ecology was gained. These models used hydraulic modeling and species- and lifestage-specific habitat preferences to determine quantity and quality of habitat as a function of streamflow. (3) Individual-based models have emerged in the 1990's as further understanding of fish life-processes has accumulated; these models track the daily actions and movements of individual organisms. The State of Georgia currently uses a variety of discharge-based methods to determine minimum allowable streamflows. The opportunity now exists to utilize many new technologies to integrate ecological and other "traditional" objectives in a real-time, operational decision support system. The principal technologies to be exploited include the ELQG algorithm, individual-based models, computational fluid dynamics, and geographic information systems.

INTRODUCTION

Fish and other aquatic organisms have often been the forgotten losers in the history of water resources development projects. Georgia and adjacent states are home to twenty-three riverine fish species currently listed as threatened or endangered (U.S. Fish and Wildlife Service [FWS] 1996). Recreational and commercial fisheries, while not at risk of complete elimination, have also suffered with accompanying economic losses; for example, the fate of the Apalachicola Bay shellfish industry has been a major issue in the on-going "water wars" between Georgia, Florida, and Alabama. While much ecological damage has been caused by the presence of reservoirs (i.e., their inundation of former habitat area and blockage of migration routes), reservoir operational policies are often also to blame for harm to fish populations. Decision-makers have sought input from life-scientists in hopes of including riverine ecology in the formulation of reservoir operations, but inadequate knowledge and understanding by all parties have often prevented the decision-making process from significantly protecting and nurturing downstream faunal communities. However, new technologies may offer improved understanding of fish populations and the ability to better comprehend the effect of reservoir operations on these populations. This paper will trace the history of riverine fish ecology modeling and then propose a decision-support system for management of ecological objectives alongside more traditional reservoir operational goals.

THE EVOLUTION OF FISH ECOLOGY MODELS

The effects of dam construction and operation on aquatic organisms began to be realized during the era of massive dam construction in the 1950's and 1960's. However, appropriate biological knowledge has lagged behind engineering technology. The development of applicable methods for assessing riverine ecological state has evolved over the past two decades as this knowledge gap has continually closed. In particular, there have been three distinct phases in this evolution: discharge-based or heuristic methods, and habitat- and individual-based models.

Discharge-based Methods

Discharge-based methods developed in tandem with the concept of minimum allowable flows (MAFs) for environmental protection. The regulatory apparatus of the 1970's assumed that riverine species would be adequately protected by the maintenance of a minimum streamflow. The Tennant (1976) method proved to be a popular guideline for specification of this minimum flow (Table 1). This method was derived from ten years of observation of streams in Montana, Wyoming, and Nebraska. Tennant's principal findings were twofold: when streamflow was at or below ten percent of mean annual discharge, fish were crowded into pools and could not pass riffles due to shallow depth; at

Table 1. Tennant Method Instream Flow Recommendations

Stream Condition	Recommended Base Flow Oct-Mar (dry)	Apr-Sep (wet)
Flushing or maximum	200% mean annual discharge	
Optimum range	60 - 100% mean annual discharge	
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	10% to zero discharge	

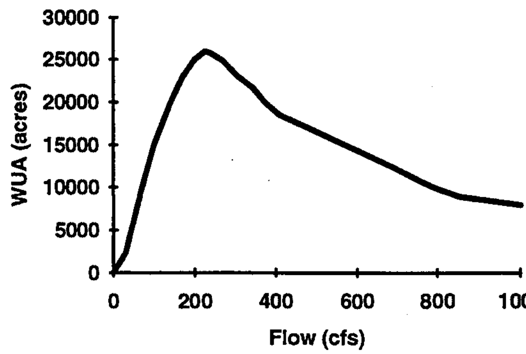

Figure 1. Habitat area as a function of discharge for chinook salmon spawners in the Tuolumne River, CA (Cardwell et al. 1996).

thirty percent of mean annual discharge the majority of the stream channel became passable. These observations, along with others, led to the general characterization of stream habitat as being determined by proportions of mean annual discharge.

While it represented an important first step in the recognition of instream flow needs for riverine life, the shortcomings of the Tennant method were many. Its categorical description of habitat condition was overly qualitative. Its reliance on a single hydrologic statistic overly simplified complex ecological adaptations to streamflow patterns. It ignored many important habitat features such as water temperature and channel substrate and biological issues such as lifestage cycles. Investigators have found the quality of its recommendations to be inconsistent when applied to streams of varying size and location (e.g., Orth and Leonard 1990).

The Tennant method was only one of many heuristic methods for recommending MAFs. Other examples include the Aquatic Base Flow method (FWS 1981) and the maximum spawning area method (Orsborn 1982). The ultimate shortcoming of this class of methods arose not from their scientific inadequacies but in the decision-making process. The MAFs seen by biologists as inviolable were regarded by decision-makers as initial negotiating positions among many other objectives. In the give-and-take of the system planning process, MAFs were often lowered to ecologically intolerable levels. Life-scientists thus recog-nized the need for quantification of the state of riverine habitat and the effects of various flow levels on the ecosystem.

Habitat-based Models

Habitat-based models were the result of increased biological knowledge and an increased understanding of the information needs of the water resources decision-making process. The development of the Instream Flow Incremental Methodology (IFIM) (Bovee 1982) and its companion computer software, Physical Habitat Simulation (PHABSIM) (Milhous et al. 1989), marked the beginning of habitat-based modeling. After intensive data collection on channel morphology, flow regime, and species- and lifestage-specific biological preferences, PHABSIM simulated the physical conditions present at thousands of specific locations in a river reach, compared these conditions to species preferences, and calculated a weighted quantity of acceptable habitat, weighted usable area (WUA). By simulating stream condi-tions at many different discharges, a continuous relationship of WUA as a function of discharge could be derived (Figure 1).

This modeling approach greatly expanded the role that life-scientists could play in developing reservoir operational policies. The effects of various plans for dam releases on downstream communities could be quantified, in the form of habitat area, and compared against each other. Thus, trade-offs between instream flows for ecological needs and other objectives could be determined. Species- and lifestage-specific analysis also allowed streamflow to be tailored to the unique time-varying requirements of downstream reaches. These strengths of the IFIM have led to its popularity in instream flow assessments.

However, the IFIM also has been found to possess many shortcomings. PHABSIM's reliance on cell-specific properties ignored many ecological mechanisms that extend beyond the spatial and temporal domain of individual cells. Factors such as predation, bioenergetics, spatial distributions of flow regime, and competitive interactions were not considered by the model. The fundamental assumption of the IFIM, that habitat availability is the principal deter-minant of ecological well-being, has also been questioned by many investigators. These shortcomings have driven the development of other habitat-based methods such as the Riverine Community Habitat Assessment and Restoration Concept (RCHARC) (Nestler et al. 1993). However, dissatisfaction with habitat-based models in general has also led to the emergence of individual-based models of fish ecology.

Individual-based models

Individual-based models were developed in the early 1990's as products of increased knowledge of the specific day-to-day biological and ecological processes of riverine fish. These processes are described with one or more mathematical equations requiring various input data. For each individual organism, the equations are computed iteratively over appropriate lifestages and temporal and spatial scales. Examples of life processes to be modeled by individual-based equations are egg incubation, foraging and growth, movement, and mortality. The models continuously track the development and location of individuals. Thus, their predictive power is greater than that of habitat-based models: at a given time individual-based models can forecast how many fish of a species will inhabit a reach, how big each fish is, how much it is eating, whether or not it will move to a new location, and whether or not it will die.

Individual-based models do possess some limitations. In order to accurately simulate all relevant life-processes for all individuals of interest, a tremendous knowledge base must be accumulated. At present, it is rare to possess a complete understanding of all life-processes. Thus, various approximations are commonly used to bridge knowledge gaps. Over time, however, these approximations can be gradually eliminated. One of the strengths of individual-based models is that they can be refined in stages due to the encapsulation of specific life-processes in distinct sets of equations; as more or better knowledge on each life-process becomes available, those mechanisms can be fine-tuned.

Another shortcoming of individual-based models is the inability thus far to quantify the uncertainty of their predictions. Most parameters of interest to decision-makers in water resources (e.g., rainfall, evaporation, hydropower demand) are easily expressed in terms of a mean and variance. Decision-makers are generally not eager to alter otherwise "optimal" policies for the sake of an additional objective when the probability of success of a change in operations is unknown. If predicted numbers and sizes of fish are to be considered in planning decisions, the potential for error must also be calculated. Field data for verification of individual-based models also appears to be somewhat lacking. Efforts to verify and calibrate models such as Jager et al. (1993 and 1996) show that the temporal extent of field data is much less than that of model predictions. While resources are undoubtedly limited for extensive field campaigns, the data to be gathered is very valuable to ensure full development of these models.

PROVISION FOR FISH IN GEORGIA

It is worth noting the manner in which riverine ecology is managed by the State of Georgia. Currently, no uniform method is used to evaluate ecological needs in the state's streams and rivers. Year-round minimum allowable flows are specified by one of two criteria. (1) Many streams have a mandated "non-depletable flow" that is determined by downstream riparian needs. These needs generally include items such as municipal withdrawals, necessary dilution of municipal and industrial wastes, and navigation requirements, but ecological needs are not explicitly considered. (2) For streams that do not have mandated non-depletable flows, the 7-day averaged minimum flow with 10-year return period (abbreviated 7Q10) is specified as minimum allowable streamflow (Department of Natural Resources [DNR] 1997). This statistical concept is a common parameter in the design of hydraulic structures for water and wastewater systems, but it has no ecological significance.

A more consistent approach may be forthcoming in Georgia. The Wildlife Resources Division of the Department of Natural Resources has issued a report that suggests a MAF equal to 30% of mean annual discharge as a "more appropriate" flow requirement (DNR 1997). This potential requirement would be in keeping with Tennant method recommendations for "excellent" stream conditions during dry periods (see Table 1).

All of the currently used and potential methods for ecological assessment are discharge-based. While the riverine ecology of Georgia (warm-water rather than cold-water species, communities of many species rather than one or two dominant species of interest) makes application of the more advanced philosophies difficult, it is important to realize that ecological analysis could be raised to more sophisticated levels. These more refined techniques would allow the quantification of trade-offs between ecological health and other objectives.

TOOLS FOR INTEGRATION OF RESERVOIR AND RIVERINE ECOLOGY MANAGEMENT

The effect of reservoir operations on downstream fish populations is and will be a significant issue in the relicense of privately operated reservoirs (e.g., Federal Energy Regulatory Commission 1996) and the revision of policies at federally owned dams (e.g., Nestler et al. 1993). While state-of-the-art technologies have been applied to aid in evaluating tradeoffs between "traditional" objectives such as hydropower, irrigation, and flood control, ecological objectives are often still assessed with inferior methods. The opportunity now exists to include fish ecology issues among other objectives in a sophisticated decision-support system (DSS) using techniques that will enable decision-makers to determine well-informed, comprehensive, and balanced policies.

Extended Linear Quadratic Gaussian (ELQG) Control

The ELQG algorithm (Georgakakos and Marks 1987) has been used to forecast optimal control policies and quantify trade-offs between objectives in real-time under uncertain future conditions. The algorithm has been applied as the backbone of a DSS for the Nile basin (Georgakakos et al. 1996a, 1996b) and other systems with significant operational success. Among objectives considered in application of the algorithm have been hydroelectric energy value, hydroelectric dependable capacity, irrigation withdrawals, water supply for domestic and industrial consumption, flood control, navigation, and downstream pollution abatement. The proven robustness and flexibility of the ELQG procedure make it an ideal candidate for including ecology among other objectives.

Individual-based Models

Despite their flaws, individual-based models represent the state-of-the-science in predicting fish ecology. The mechanistic nature of these models allows the effects of various streamflow policies to be evaluated in terms of numbers and locations of surviving individuals. The temporal and spatial effects of various policies are reflected with a quality impossible to obtain from habitat-based approaches. Individual-based models have yet to be applied in either real-time operations or in sophisticated optimization schemes, but the models' considerable predictive power coupled with reliable meteorological and hydrologic forecasts could provide detailed predictions of future ecological state. This information will enrich the trade-off analysis of a DSS and improve the available information to decision-makers.

Of course, the faults of individual-based models must be overcome. Techniques to quantify uncertainty of model predictions must be developed that are consistent with computed variability of other parameters. Gaps in the knowledge of various life-processes must be filled; replacing approximations with physically based algorithms is a definite step towards reducing uncertainty of model predictions. Extensive field data must be gathered with which to verify simulation processes. Finally, the scope of research must extend beyond the commonly investigated salmonid species. Warm-water and non-anadromous species (as well as eastern anadromous species such as the Gulf Sturgeon) which are prevalent in Georgia and the south-eastern U.S. have not received the same attention in the history of ecological modeling as endangered salmon of the Pacific coast.

Computational Fluid Dynamics

One possible improvement to the individual-based modeling approach is the use of numerical 2-D and 3-D hydraulic modeling. Almost without exception, fish ecology models of all types currently use overly simplified 1-D energy analysis of open channel flows based on Manning's equation. While this technique is certainly valid for exploratory analysis, reliable predictions of hydraulic properties at scales relevant to individual fish are impossible from 1-D analysis (Leclerc et al. 1995). Computational fluid dynamics methods now make it possible to dependably model depth, velocity, and thermal properties for vertically integrated 2-D and fully 3-D flows. Since both habitat-based and individual-based schemes rely to some degree on determining satisfaction of species- and lifestage-specific hydraulic preferences, improving knowledge of hydraulic properties can only improve the forecasts of fish ecology models.

Geographic Information Systems

Finally, geographic information systems (GIS) coupled with the graphical user interface (GUI) common to well-developed DSSs can add an additional facet to the quality of information available from an integrated DSS. Common habitat-based analyses often oversimplify ecological reality by ignoring the spatial distribution of habitat characteristics. Use of a GIS allows for the spatial presentation of the physical characteristics of stream reaches (e.g., substrate, depth), input data to the fish ecology model (e.g., spawner numbers and locations), and model predictions (e.g., nesting sites and numbers of surviving eggs at a later time). The advantages of such presentation are many; for example, the expected location of an endangered species population relative to public and private lands or a potential waste outfall could be observed.

CONCLUSION

It is these primary technologies -- (1) ELQG control, (2) individual-based models, (3) computational fluid dynamics, and (4) geographic information systems -- along with other supporting technologies, that hold the most potential for a tool for integrated reservoir and riverine ecology management. The product of combining these techniques will be an advanced tool for forecasting the state of water resources systems and contiguous riverine ecosystems, searching for best possible control policies that sufficiently meet all relevant objectives, and evaluating the trade-offs between objectives in terms of time, location, and resources.

The time is right for a pilot study to integrate ecological objectives into a multi-objective reservoir system management framework. Georgia Tech's Water Resources Group possesses the expertise to apply the technologies listed above, but the weaknesses of the current state of individual-based models limit the potential effectiveness of an integrated decision support system. Collaboration between Georgia Tech and a group able to refine individual-based models to an appropriate level would yield a truly integrated and powerful tool. Such a system would be a tremendous step in the efforts that have been ongoing for three decades to include riverine ecological needs in water resources management.

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